Use of Travel Demand Model Data to Improve Inventories in Philadelphia

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ABSTRACT

Highway emissions represent a major source of many pollutants. Use of local data to model these emissions can have a very large impact on the magnitude and distribution of emissions, and can significantly improve the accuracy of local scale air quality modeling assessments. This paper provides a comparison of "top-down" and "bottom-up" approaches for developing emission inventories for modeling in one urban area, Philadelphia, in calendar year 1999. A "bottom-up" approach relies on combining motor vehicle emission factors and vehicle activity data from a Travel Demand Model (TDM) estimated at the road link level to generate hourly emissions data. This approach can result in better estimates of levels and spatial distribution of onroad motor vehicle emissions than a "top-down" approach, which relies on more aggregated information and default modeling inputs.

INTRODUCTION

The first step in developing an emission control strategy is to develop an inventory that lists all sources of the pollutant and its precursors, and the amount emitted of each pollutant by these sources. For emission inventory development, the U. S. Environmental Protection Agency categorizes emissions into several source types: stationary, mobile, and biogenic. Stationary sources are further divided into major and area sources. Major sources are those with emissions that exceed a minimum or threshold level, which varies by pollutant. Stationary sources that fall below that level are merged into source categories as area sources. Mobile sources include highway vehicles and nonroad engines (e.g., lawn and garden equipment, recreational vehicles, construction equipment, commercial marine vessels, locomotives, and aircraft). Biogenic sources include plants, trees, agricultural animals and crops. Highway vehicle emissions represent a major source of many pollutants in the United States. In this paper we will focus on air toxics emissions from highway vehicles only.

Highway emission factors are usually estimated using models which are based on emission measurements. An example of such a model is U. S. EPA's MOBILE6.2 emission factor model[1], which estimates exhaust and evaporative emission factors for various types of vehicles under a given set of conditions in grams or milligrams per mile. Conditions that affect these emission factors, and which are described in the form of model inputs, include ambient temperature, speed, age of the fleet, whether an area has an inspection and maintenance program, and types of fuels used. Emission factors are then multiplied by vehicle miles traveled for a given modeling domain to develop an inventory:

Equation (1) $E_i\,(s) = EF_i\,\,(s) \times A\,(s)$

where:

Ei (s) = Emission rate (mass per unit of time) for pollutant i from a source s
EFi (s) = Emission factor (mass per unit of activity) for pollutant i from source s
A(s) = Activity level for source s (e.g.,vehicle miles traveled) over a given time

Highway vehicle emission rates for regional and national scale air toxics assessments are usually developed using a "top-down" approach. For these applications, emission factors are assumed to represent long term vehicle population averages for a given vehicle class, and are often based on default or average inputs. Furthermore, activity data are allocated from a larger geographic scale (State, or urban area) using spatial surrogates such as population. The county-level emissions inventory is then estimated as the product of emission factors and activity. Other spatial surrogates are used to allocate county level emissions to grid cells or census tracts as required by the air quality model.

This "top-down" approach is taken due to the difficulty of gathering and incorporating more precise local data for such a large domain. A limitation of this approach is that default inputs used to estimate emission factors, or activity allocated from a larger geographic scale, may not reflect local scale conditions. Thus, "top-down" inventories, which are practical for national scale applications, can mischaracterize emissions at the individual county and sub-county (local) scales.

More accurate local scale emission rates can be developed using a "bottom-up" approach, which relies on using more local inputs to estimate better emission factors and vehicle activity data from a Travel Demand Model (TDM). TDM data used for transportation planning can provide more detailed information on the spatial distribution of roadway types, vehicle activity, and speeds along those roads. These data can be used to more accurately estimate the emission rates at the local scale, as well as where they occur, thus providing better estimates at the census tract level.

An example of an assessment which uses the "top-down" approach is the U. S. EPA's National-Scale Air Toxics Assessment.[2] The National Scale Air Toxics Assessment relies on data from the U. S. EPA's National Emissions Inventory (NEI), a national database of air pollutant emissions for major and area stationary sources, highway vehicles, and nonroad equipment.[3]

Large-scale air toxics assessments, such as the National-Scale Air Toxics Assessment, are very useful as screening tools, and for identifying priorities for further analysis. The National-Scale Assessment has also been used for a variety of purposes which could be impacted by a mischaracterization of emissions at the local scale, such as evaluation of socioeconomic and racial disparities in risk in an urban area.[4, 5] Indeed, the level and distribution of toxic emissions estimated for an urban area using a "top-down" approach vary greatly with estimates produced based on localized data. This can in turn affect the modeled concentrations and estimated risk. A recent study conducted in the Minneapolis-St. Paul area of Minnesota, which used spatial surrogates to allocate mobile source emissions to census tracts, found that the dispersion model used tended to overpredict at low monitored concentrations, and undepredict at levels of high monitored concentrations.[6] The investigators attributed this pattern to the failure to represent roadway emissions properly.

Recent studies[7,8] show that using more refined local activity data to allocate emissions can improve model performance and have a significant impact on how toxic emissions are distributed in an urban area. These studies also show that there are strong spatial gradients of toxic emissions associated with roads, and that the high levels of air toxics associated with roads may increase risks for a number of adverse health effects. Thus, more accurate emissions data at the local scale is important in developing strategies to address air toxics at the local level.

In this study, activity level data from travel demand modeling were used in conjunction with emission factor data from the U. S. EPA's MOBILE6.2 model to develop a highway vehicle air toxics inventory that provides emission estimates at the highway link-level by county for the Philadelphia metropolitan area. These results were then compared with county and census tract emissions inventories developed for the 1999 National Scale Air Toxics Study.[2] This paper focuses on primary emissions of the following pollutants -- benzene,1,3-butadiene, formaldehyde, acetaldehyde, and acrolein. Benzene is a product of both exhaust and evaporation while the other air toxics are only a product of exhaust. Formaldehyde and acetaldehyde are secondarily formed in the atmosphere, but these contributions are not included in the emission totals here.

METHODOLOGY

Development of a Highway Emission Inventory for National Scale Assessments: the "Top-Down" Approach

Development of Emission Factors – For its National Emissions Inventory, U. S. EPA calculated air toxic emission factors for highway vehicles using EPA's MOBILE6.2 emission factor model.[9,10] In addition to modeling criteria pollutant emission factors, MOBILE6.2 estimates emission factors for the air toxics discussed in this paper. Modeling these pollutants requires detailed information on fuel parameters as inputs, along with other inputs such as roadway type, average temperature, altitude, and inspection maintenance program, which are also required to model criteria pollutant emissions. Emission factors for other air toxics can be estimated using a command which allows the user to enter emission factors or air toxic ratios for additional air toxic pollutants.

In the development of the 1999 NEI, the U. S. EPA used national default values for certain key modeling inputs to MOBILE6.2, such as vehicle registration distributions by age, the fraction of VMT for each class of vehicles, and vehicle speeds for different roadway types (e.g., freeways, arterials, local roads, connector ramps) were used. For fuel inputs to MOBILE6.2, such as average benzene and aromatics level, RVP, and oxygenate type and level, the NEI utilized data from fuel surveys done at service stations.[10,11] In some cases, survey data specific to individual cities are available, while for many parts of the U.S., only aggregated regional data are available.

As a further refinement, emission factors are calculated by season, road type, and vehicle type, for exhaust and evaporative emissions.[11] Categories of exhaust and evaporative emissions include:

- Exhaust start emissions
- Exhaust running emissions
- Crankcase emissions – emissions that leak past the piston rings into the crankcase but are not captured due to disabled PCV (positive crankcase ventilation) systems
- Evaporative diurnal emissions -- emissions that are caused by the change in ambient temperature over the course of a day while a vehicle is parked
- Evaporative hot soak emissions -- emissions that are produced immediately after a vehicle is stopped and the engine is turned off.
- Evaporative resting loss emissions -- emissions that result from leaks or permeation of gasoline when the vehicle is off.
- Evaporative running loss emissions -- emissions that are produced due to heat build-up in the fuel during vehicle operation.

For the NEI, state, local and tribal agencies sometimes replace U. S. EPA-generated emission estimates with their own emission estimates by submitting the data to U. S. EPA during the NEI development or review stages. The preferred method, however, is for the state, local and tribal agencies to provide inputs to the National Mobile

Inventory Model,[12] the framework housing MOBILE6.2. This allows more local data to be used in a more transparent way.

Development of County Activity Level -- To develop county level VMT for large urban areas such as Philadelphia, U.S. EPA relies on aggregate statistics compiled for the entire urban area, and supplied by the Federal Highway Administration (FHWA), part of the U. S. Department of Transportation.[11,13] These data include VMT for the urban area by roadway type, and VMT by vehicle type at the National level. Using these data, VMT for the Philadelphia urban area by roadway and vehicle type were estimated. Then, these VMT for the entire urban area were allocated to the county/roadway level using Bureau of the Census 1990 Number of Inhabitants (CNOI) data at the county level.[14] The following equation was used:

Equation 2 $$VMT_{UX,C} = VMT_{UX,A} \times \frac{POP_{UX,C}}{POP_{UX,A}}$$

where:

$VMT_{UX,C}$	= Urban area VMT on roadway type X in county C (calculated)
$VMT_{UX,A}$	= Urban area VMT on roadway type X for total urban area A contained in state (FHWA)
$POP_{UX,C}$	= Urban area population in county C with nonzero mileage from urban roadway type X
$POP_{UX,A}$	= Urban area population for total urban area A contained in state totaled for all counties with nonzero mileage from urban roadway type X

Using the methodology in Equation 2, county level VMT could be overestimated for areas where average VMT per capita is lower than average, such as urban centers with mass transit, and underestimated in areas where people tend to travel more, such as suburban areas. Finally, county-level annual VMT was temporally allocated to different seasons using National seasonal allocation factors.[11]

Development of a County Level Emissions Inventory -- Using the emission factors and activity level (VMT) developed in the above steps, Equation 1 was used to develop a county level inventory, with inventory estimates by emission type, vehicle class, roadway type, and season.

Allocation of Total Highway Vehicle Emissions to Census Tracts – County level highway vehicle air toxic emissions from the NEI are allocated to census tracts or grid cells for national or regional scale modeling using the Emission Modeling System for Hazardous Air Pollutants (EMS-HAP).[15] EMS-HAP allocates highway vehicle emissions using the following equation:

Equation 3 $$E_{tract,county,J} = E_{county,J} \times S_{tract,county,J}$$

where:

$E_{tract,\ county,j}$	= census tract or grid cell emissions from source category j in a county
$E_{county,\ j}$	= emissions from category j in county that contains census tract or grid cell.
$S_{tract,\ county\ j}$	= spatial allocation factor for tract or grid cell in county that corresponds to spatial surrogate assigned to source category j.

While there are twelve different roadway types in the NEI, only six different spatial surrogates representing road miles for different roadway types are available for allocation to census tracts nationwide. Thus, county-level emissions for the twelve roadway types in the NEI must be matched with these six surrogates in order to allocate emissions to census tracts. Table 1 shows how highway vehicle categories are mapped to these six spatial surrogates. Roadway miles are used as a surrogate for all categories but local roads, and population is the surrogate for local roads. The surrogates were developed using data from a digital database maintained by the U.S. Bureau of Census known as TIGER (Topologically Integrated Geographic Encoding and Referencing system). They are described in Table 2. These surrogates were used to estimate census tract level emissions in Philadelphia.

Table 1. Mapping of Mobile Source Emission Roadway Categories to Spatial Surrogates

Highway Mobile Source (FHWA category)	Spatial Surrogate Assignment
rural interstate	rural primary road miles
rural other principal arterial	rural primary road miles
rural minor arterial	rural primary road miles
rural major collector	rural secondary road miles
rural minor collector	rural secondary road miles
rural local	rural population
urban interstate	urban primary road miles
urban other freeways and expressways	urban primary road miles
urban other principal arterial	urban primary road miles
urban minor arterial	urban primary road miles
urban collector	urban secondary road miles
urban local	urban population

Table 2. Data Used to Develop Surrogates for Mobile Sources for National/Regional Scale Modeling.

Surrogate	Description of how surrogate was developed
Urban Primary Roads	Road Miles of Urban Primary Roads. Overlayed US Census Bureau's urban areas with TIGER (Topologically Integrated Geographic Encoding and Referencing system) roads. Urban primary roads are roads with CFCC (census feature class code) A11 through CFCC A28 and A63 that fall within census designated urban areas.
Rural Primary Roads	Road Miles of Rural Primary Roads. Overlayed US Census Bureau's urban areas with TIGER roads. Rural primary roads are roads with CFCC A11 through CFCC A28 and A63 that fall within census designated rural areas.
Urban Secondary Roads	Road Miles of Urban Secondary Roads. Overlayed US Census Bureau's urban areas with TIGER roads. Urban secondary roads are roads with CFCC A31 through CFCC A38 that fall within census designated urban areas.
Rural Secondary Roads	Road Miles of Rural Secondary Roads. Overlayed US Census Bureau's urban areas with TIGER roads. Rural secondary roads are roads with CFCC A31 through CFCC A38 that fall within census designated rural areas.

Development of a Highway Emissions Inventory for Local Scale Assessments: the "Bottom-Up" Approach

Metropolitan Planning Organizations (MPOs) in the U. S. are transportation policy-making organizations made up of representatives from local government and transportation authorities. One of an MPO's functions is to develop long-range transportation plans for the urban area. Travel Demand Models (TDMs) are commonly used to predict the demand for transportation services such as roads and to assist in the development of alternative plans. These models use a link-node network tied to geographic coordinates to characterize travel patterns in the urban area. Associated with this network are data attributes such as number of lanes, roadway type, volume, speed, and capacity. These activity data can be used with the emission factors from the MOBILE6.2 model to create detailed, spatially distributed emission rates at the local level.

In this study, the geographic database and associated attribute data of the Philadelphia area roadway network were obtained from the Delaware Valley Regional Planning Commission. The data were developed using the TRANPLAN

TRANsportation PLANning integrated model developed by Citilabs. This database contains information on all roads, except local roads, based on 1999 information. Each road is divided into links and nodes which are road segments and endpoints. Information provided includes coordinates of the nodes, roadway type, directional average annual daily traffic (AADT) values, and number of lanes.

This network data was first projected into Universal Transverse Mercator (UTM) coordinates such that each roadway segment, or link, in the database consisted of x and y coordinates, a roadway type indicator, directional AADT values, and number of lanes. Directional AADT values were summed and multiplied by the roadway segment length to obtain daily Vehicle Miles Traveled (VMT) values. VMT by season and hour of the day was then estimated using temporal distributions from the Delaware Valley Regional Planning Commission and allocated to vehicle classes.

EPA's MOBILE6.2 model was used to create seasonal, fleet average emission factors for Philadelphia counties (in grams/mile). The seasonal fleet average emission factors output from MOBILE 6.2 varied by facility type (freeway, arterial, local, ramp) and emission type (exhaust running, exhaust start, evaporative hot soak, evaporative diurnal, evaporative resting loss, evaporative running loss, and crankcase). The same average speed distribution and fraction of total VMT for individual vehicle classes were used for all links of a given facility type. Emission factors for running emissions (emissions produced from engine exhaust and evaporation as the engine is running) were extracted from the output by season and facility (arterial, interstate), and matched to the VMT for links (Nonrunning emissions are not associated with activity on road links and were handled differently, as discussed later). This yields the hourly running emissions for each of the air toxics for individual links:

Equation 4 $$E_{county,J} = \sum FAC_{county,J} \times VMT_{county,J}$$

where:

$E_{county,j}$ = seasonal, hourly link running emissions (mass per unit of time) from facility j in a county

$FAC_{county,j}$ = seasonal fleet average running emission factor (mass per unit of activity for running exhaust, crankcase, and running evaporative) for facility type j within each county

$VMT_{county,j}$ = seasonal, hourly link activity (VMT) for facility type j within each county

Nonrunning (evaporative emissions produced while the motor vehicle is not running or exhaust emissions from engine starting) emission rates were derived from applying the MOBILE6.2 nonrunning emission factors (exhaust start, evaporative hot soak, evaporative diurnal, evaporative resting loss) to total county VMT by hour, and were then spatially distributed to 1km x 1km grids using surrogates such as gridded interstate and other roads. Gridding surrogates were developed by calculating the ratio between the length of roadway in a 1km square modeling grid and the total length of roadway in a county. These ratios were then used as surrogates to spatially distribute the total county emissions to the individual grid cells. Total vehicle emissions for counties are the sum of all link level running emissions and county level nonrunning emissions.

RESULTS

Differences in Spatial Distribution of Emissions

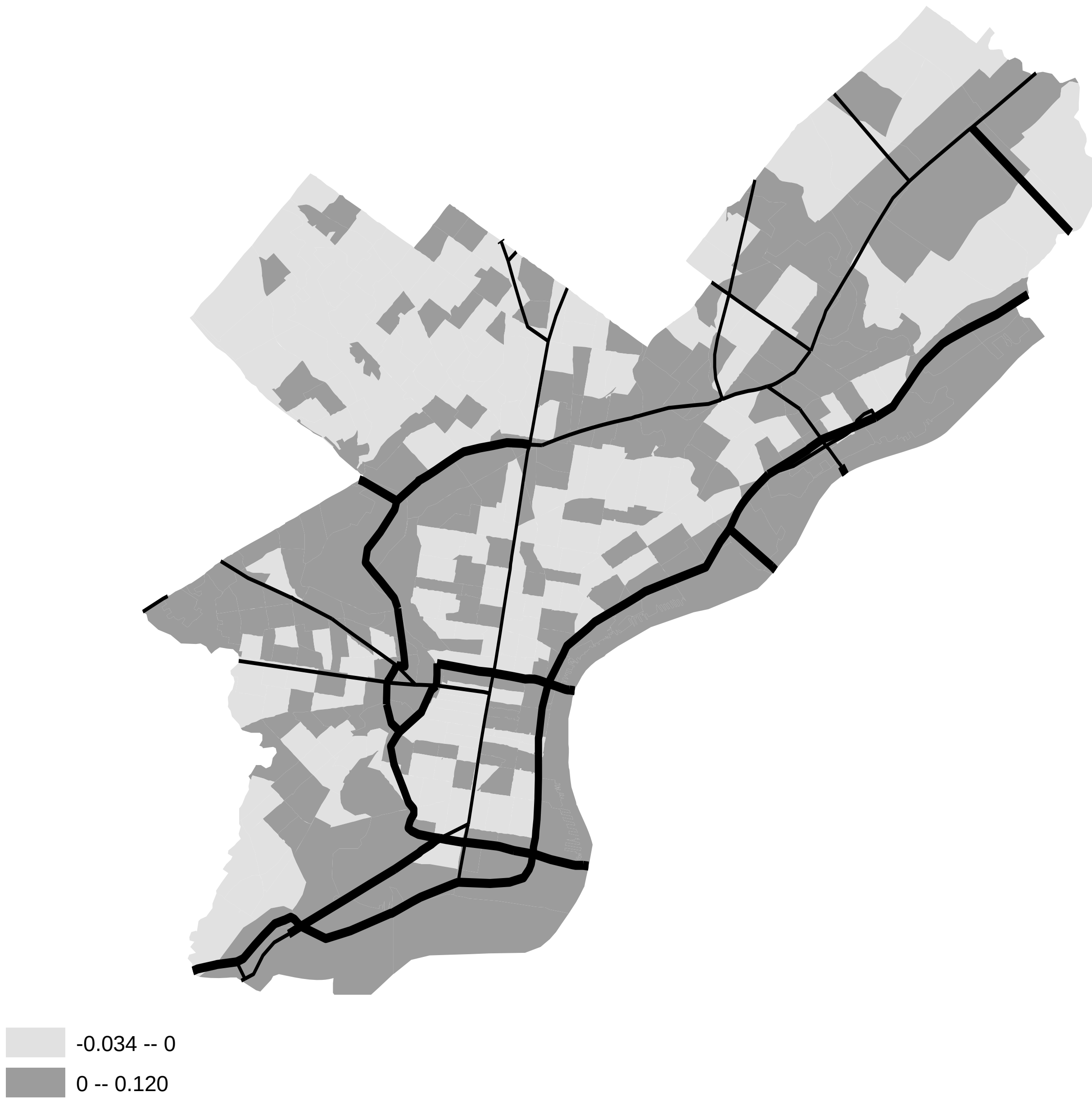
Both the spatial distribution of emissions and the total county emissions differ significantly between the “top-down” and the “bottom-up” methodologies described above. Differences in the spatial distribution of emissions between the two methodologies is shown in Figure 1. Link based emissions were aggregated to tracts for the purpose of this comparison.

Differences in Magnitude of County Level Emissions

Using the two approaches, the total county level emission inventories for air toxics vary significantly for the modeling domain. Table 3 compares benzene emissions using the two approaches. Philadelphia county benzene emissions using the “bottom-up” approach are about half of the emissions derived from using the “top-down” approach. A similar difference is seen for other air toxics (Table 4).

Most differences in emissions among counties between the two approaches can be explained by examining the VMT, summarized in Table 5. While individual county level VMT varies greatly, the summed total VMT for all the counties in the Philadelphia metropolitan area is close. The individual county differences are a direct result of the approaches used. The “top-down” approach allocates VMT to the individual counties in an urban area based on population ratios (Equation 2) while the “bottom-up” uses actual traffic count data (e.g., VMT) for each roadway segment in a county to arrive at total county emissions (Equation 4).

Figure 1
Difference in Emissions Density (1999 NATA "Top-Down" Versus "Bottom-Up" Approach Using Link Based Emissions)



Tons/Year/Sq. Mile

Table 3. Comparison of Annual 1999 Benzene Emissions (tons/year) from Two Approaches (TDM = Travel Demand Model; NEI = National Emissions Inventory).

County	"Bottom-Up" TDM	"Top-Down" NEI	Percent Difference
Camden	165	210	-27%
Delaware	162	160	1%
Gloucester	110	104	6%
Montgomery	333	209	59%
Philadelphia	255	467	-45%
Total	1,025	1,150	-12%

Table 4. Comparison of Annual 1999 Emissions (tons/year) for Selected HAPs Using the Two Approaches (TDM = Travel Demand Model; NEI = National Emissions Inventory).

County	Butadiene, 1,3-		Formaldehyde		Acetaldehyde		Acrolein	
	"Bottom-Up" TDM	"Top-Down" NEI	"Bottom-Up" TDM	"Top-Down" NEI	"Bottom-Up" TDM	"Top-Down" NEI	"Bottom-Up" TDM	"Top-Down" NEI
Camden	25	34	93	128	29	37	4	6
Delaware	21	26	79	105	24	30	3	4
Gloucester	17	17	62	66	19	19	3	3
Montgomery	44	35	165	139	51	40	7	6
Philadelphia	34	77	127	305	39	86	5	13
Total	141	189	526	743	162	212	22	32

Table 5. Comparison of Annual VMT From Two Approaches.

	Annual VMT (Vehicle Miles Traveled)		
	1999		
County	VMT Derived from TDM (Travel Demand Model) "Bottom-Up"	VMT From Highway Statistics (used in NEI) "Top-Down"	Percent Difference
Bucks	4,878,636,990	3,710,307,400	31%
Burlington	4,187,820,178	3,567,877,700	17%
Camden	3,682,826,156	4,199,354,700	-12%
Chester	4,491,670,453	3,046,058,600	47%
Delaware	3,155,112,296	3,373,141,300	-6%
Glouster	2,524,701,655	2,195,654,200	15%
Mercer	3,136,953,593	3,555,648,300	-12%
Montgomery	6,381,619,077	4,508,702,800	42%
Philadelphia	4,864,568,590	9,804,935,300	-50%
Total	37,303,908,988	37,961,680,300	-2%

However, despite the fact that summed VMT for the Philadelphia metropolitan area is similar between the two approaches, the total "top-down" benzene inventory for counties entirely within the modeling domain is about 12% higher than the "bottom-up" approach (Table 3). This indicates that the MOBILE6.2 inputs used in the "bottom-up" approach are also playing a role, and the differences are attributable to exhaust emissions, rather than evaporative. This is because the differences are even more pronounced for the air toxics in Table 4, which do not have an evaporative component, than they are for benzene. Potential causes of the differences can be identified from a sensitivity analysis of criteria pollutant estimates done for MOBILE6.2, which indicated that the following inputs (which directly relate to exhaust emission estimates) had a large impact on emission factors: speed, registration distribution, VMT fractions for individual vehicle classes, temperature, and RVP.[16] Thus, we explored the impacts these key inventory inputs had on benzene emission results using the two approaches.

Small increases in the fraction of vehicles traveling at low speeds can have a large impact on emissions. Thus, we also compared speed inputs between the NEI and the "bottom-up approaches for Philadelphia. For default MOBILE6.2 runs, such as those done for the NEI, an AVERAGE SPEED command is used. With this command, the VMT are assigned to two speed ranges for freeways and one speed range for arterials. In the Philadelphia "bottom-up" modeling, the MOBILE6 SPEED VMT command was used, which assigns VMT to 14 speed ranges for both freeways and arterials. A comparison of emission rates using the SPEED VMT command versus the AVERAGE SPEED command at various average speeds found very little difference in results for benzene.

The registration distributions used in the "bottom-up" approach can also have a large impact. A 20% shift in vehicle fractions among age classes can lead to an increase in emissions of up to 50%.[16] A comparison of benzene emission factors for Philadelphia County, using local distributions versus the MOBILE6.2 defaults, with all other inputs unchanged, had a significant impact. Emission factors were more than 12% to 14% lower using the local distributions (Table 6).

Table 6. Impact of Local Registration Distribution on MOBILE6 Benzene Emission Factors (All Other Inputs Unchanged)

		Emission Factor (gm/mi)		
Facility	**Speed**	**Local**	**M6 Default**	**% Difference**
Arterial	10	64	74	-13
Arterial	15	51	59	-13
Arterial	20	44	51	-14
Arterial	25	41	47	-14
Arterial	30	38	44	-13
Arterial	35	37	42	-13
Arterial	40	36	42	-13
Arterial	45	36	41	-13
Freeway	10	61	71	-14
Freeway	15	47	55	-14
Freeway	20	43	49	-14
Freeway	25	40	47	-13
Freeway	30	39	45	-13
Freeway	35	38	43	-13
Freeway	40	37	43	-13
Freeway	45	37	42	-12
Freeway	50	37	42	-12
Freeway	55	37	42	-12
Freeway	60	37	41	-12
Freeway	65	36	40	-12

The third input which varied between the "bottom-up" approach and the "top-down" approach used in the NEI was the fraction of the total VMT assigned to individual vehicle classes. However, a comparison of the impact of using local VMT fractions on benzene emission factors in Philadelphia County, with all other inputs unchanged, found this had little effect (about 0.6%). Other inputs which have been found to significantly impact toxic emission factors, such as temperature and RVP, did not vary between the two modeling approaches. Thus, we concluded that differences in registration distributions between the two approaches explain a significant portion of the total inventory difference for the modeling domain.

CONCLUSION

Use of local level inputs can have a significant impact on both the distribution and the magnitude of highway vehicle air toxic emissions. This study shows that estimating vehicle emissions for individual road links to develop an inventory results in a much different spatial distribution of emissions than allocating emissions using spatial surrogates. Furthermore, the population ratio methodology used to allocate VMT to counties in the U. S. National Emissions Inventory results in a much different magnitude of emissions at the county level than the “bottom-up” methodology which relies on travel demand model estimates of where this activity is occurring. Moreover, use of local data rather than the default national inputs in emission factor models typically used to develop “top-down” inventories can also result in significant differences in the magnitude of air toxics emissions estimates at the county level. In the case of Philadelphia, using local registration distribution data in the MOBILE6.2 emission factor model results in significantly lower air toxics emission factors and resultant emission inventories than obtained using national defaults. In addition to improving the quality of local scale assessment, using these local data can improve the quality of regional and national level emission inventories. Use of local inputs and aggregated VMT from travel demand models with the “top-down” approach used in the U. S. Environmental Protection Agency’s National Emissions Inventory results in county-wide inventories which closely approximate county-wide inventories developed using a more disaggregate “bottom-up” approach.

ACKNOWLEDGEMENTS

We would like to acknowledge the contribution of Ray Chalmers, Dr. James D. Smith, Brian Rehn and Alan Cimorelli of EPA Region 3, and Megan Beardsley, and Chad Bailey of EPA’s Office of Transportation and Air Quality. We also appreciate the comments of Laurel Driver, George Pouliot, and William Benjey.

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KEY WORDS

MOBILE6.2
Travel Demand Model
National Emissions Inventory
National-Scale Air Toxics Assessment
Highway Vehicles
Emissions Allocation